Development of Ultrasonic Methods of Hemodynamic Measurements

Michael B. Histand
Francis D. McLeod
Charles W. Miller

Departments of Mechanical Engineering and
Physiology and Biophysics
Colorado State University

(NASA-CR-143458) DEVELOPMENT OF ULTRASONIC METHODS OF HEMODYNAMIC MEASUREMENTS (Colorado State Univ.) 37 p HC $3.75 CSCL 06B
N75-31714
Unclas
G3/52 35260

A Technical Report
Prepared for the
National Aeronautics and Space
Administration

Ames Research Center
NASA Grant NSG-2009

August 1, 1975

CONTENTS

I. SAMPLE FUNCTION AND DIAMETER MEASUREMENT

1. Sample Function Calculation

The sample function of the PUDVM can be measured experimentally as a step velocity response. As the sample region scans a zero velocity/high velocity interface the recorded RMS power from the audio signal can be used to calculate the effective length of the sample function. For $R_{transducer} < R/2_{vessel}$, this method provides an accurate measure of the sample function length since the experimental constraint is that the step be abrupt compared to the resolution of the ultrasound system. For these determinations flow in the vessel is maintained at RE=4000 to insure a blunt profile and therefore steep velocity gradient at the wall. The abruptness of the experimental test function can be estimated from the minimal velocity to which the instrument will respond and the velocity gradient dv/dr at the wall. Assuming a turbulent velocity profile:

$$V = V_o \left(1-\left(\frac{r}{R}\right)^4\right)$$

and

$$\frac{dV}{dr} = V_o \; 4\left(\frac{r}{R}\right)^3$$

where V_o is the peak velocity and r/R is the nondimensional radius. The velocity gradient at r/R equal to 1 is:

$$\left.\frac{dv}{d\left(\frac{r}{R}\right)}\right|_{r/R=1} = -4V_o$$

The minimal sensible velocity of the current PUDVM design (McLeod 1974) is on the order of 1cm/sec. A typical V_o = 50 cm/sec. The abruptness of the step $\Delta\left(\frac{r}{R}\right) = \frac{1}{200}$. The 1/200 fractional radius step abruptness

is far steeper than the instrument resolution and can therefore be considered ideal.

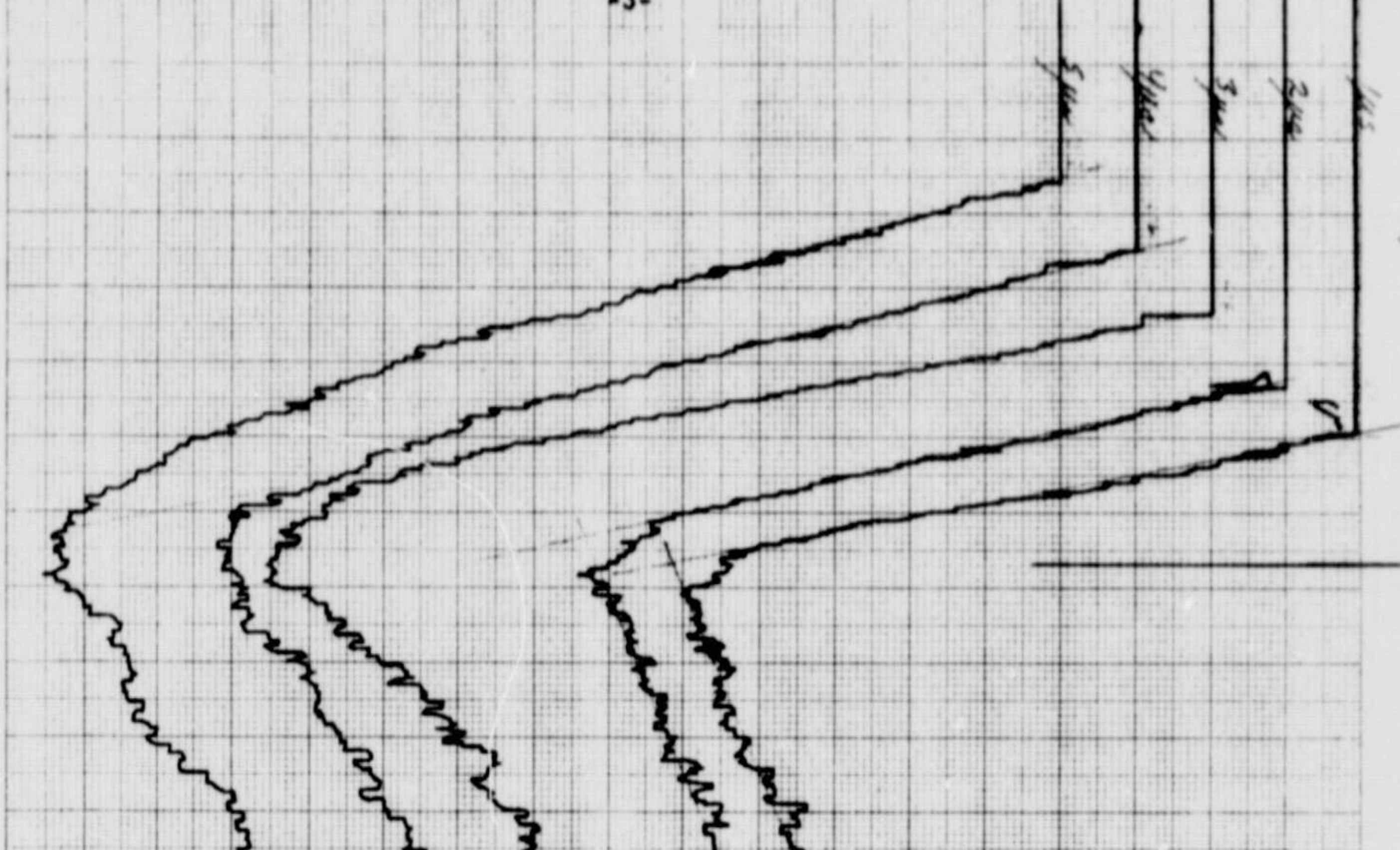
Figures 1 and 2 exhibit RMS voltage curves for a transducer diameter equal to $(R/2)_{vessel}$ as the sample function is scanned across the vessel. Each successive curve is obtained by increasing the gate setting from 1 μsec to 8 μsec in 1 μsec increments. The sample function is obtained as indicated by calculating the delay times of the rise of the RMS voltage from zero to its peak. To be most precise the voltage curves should be converted to power curves. For a gate setting of 1 μsec the sample function is 1.8 μsec implying a length Lg of

$$Lg = \frac{\tau_g \cdot 1500\text{m/sec} \cdot \sin(60°)}{2} = 1.16\text{mm}$$

Therefore gate settings can be easily found to provide sample function lengths of R/2, R, 3R/2, 2R for the experiments to be described.

2. Measurement of Vessel Diameter

Vessel diameter can be measured accurately by recording audio power during a sample function scan of the vessel cross-section. The half power points at the near and far slopes correspond to the locations of the walls of the vessel, since half power assumes the centroid of the sample function is at the wall-fluid interface. An example of a half power scan for transducer R/2 for the four different gates is shown in Figure 3. Note that the measured diameter is 7.3 mm which is within 5% of the actual vessel diameter. Note also the poor wall discrimination for a gate greater than R/2.



RMS VOLTAGE VS. RANGE

TRANSDUCER DIAMETER = R/2 (1.9mm)

RE = 4000

FIGURE 1

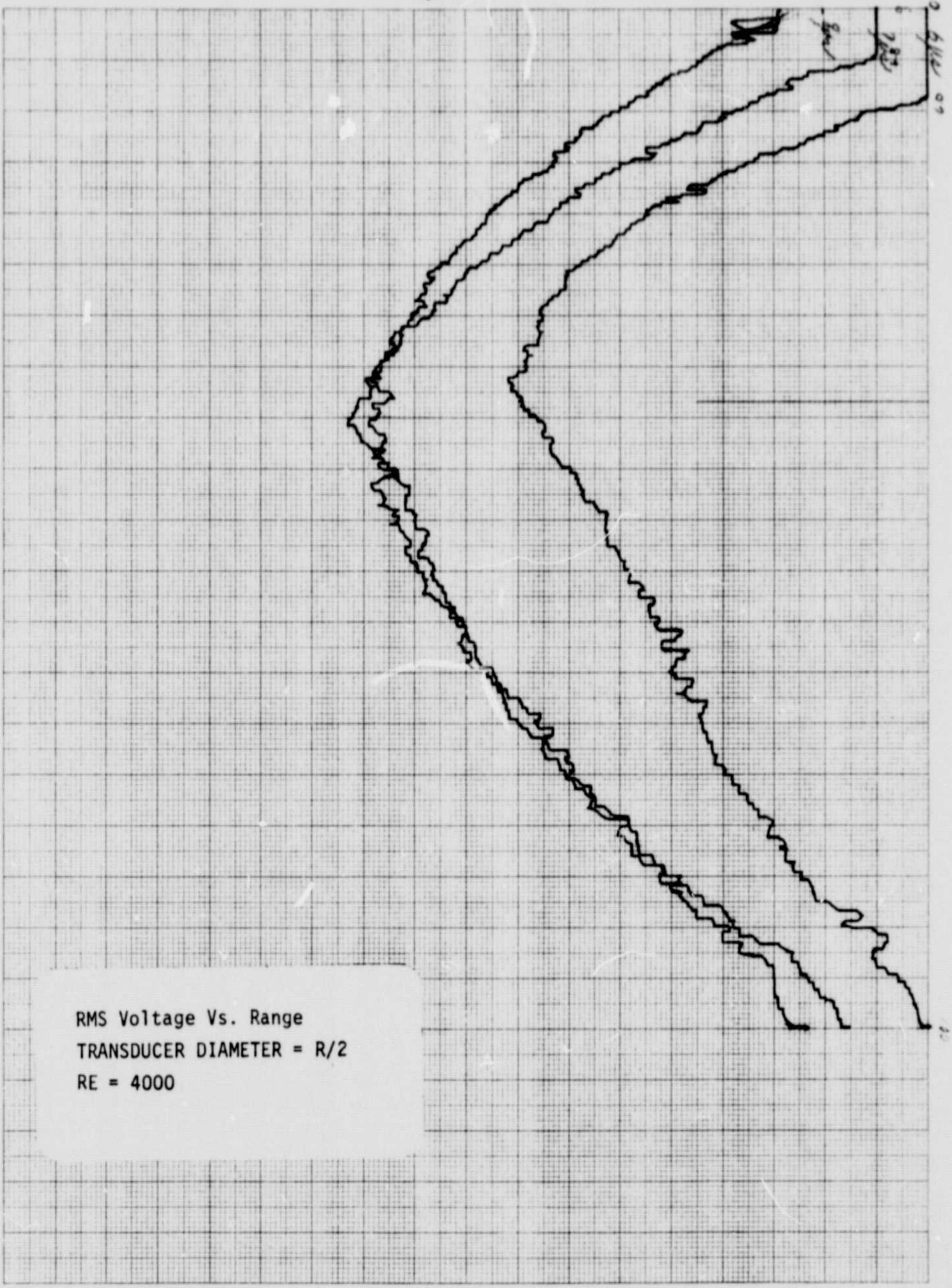
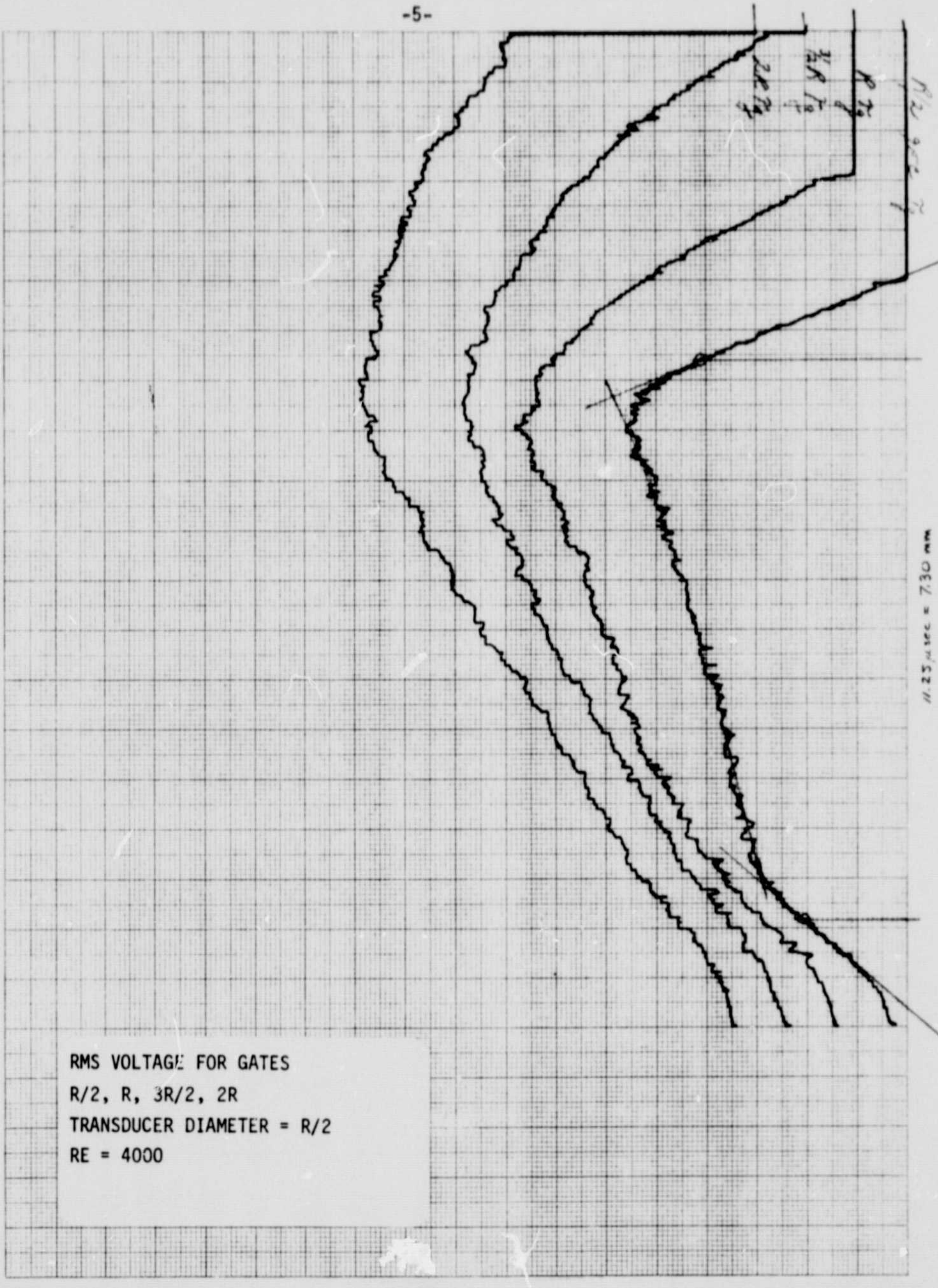


FIGURE 2



RMS VOLTAGE FOR GATES
R/2, R, 3R/2, 2R
TRANSDUCER DIAMETER = R/2
RE = 4000
2R T_g
3/2R T_g
R T_g
11.25 μsec = 7.30 mm
move focal point

FIGURE 3

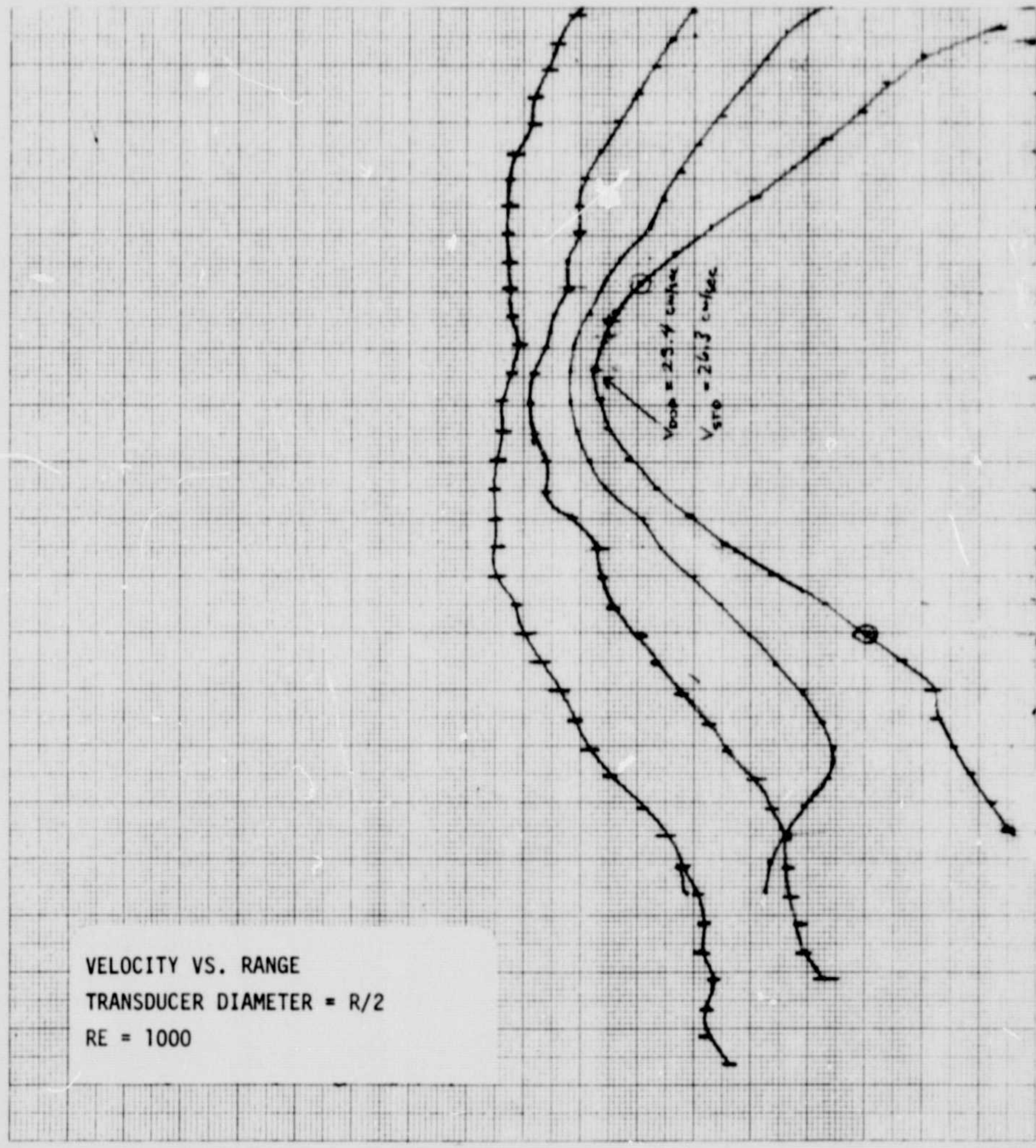
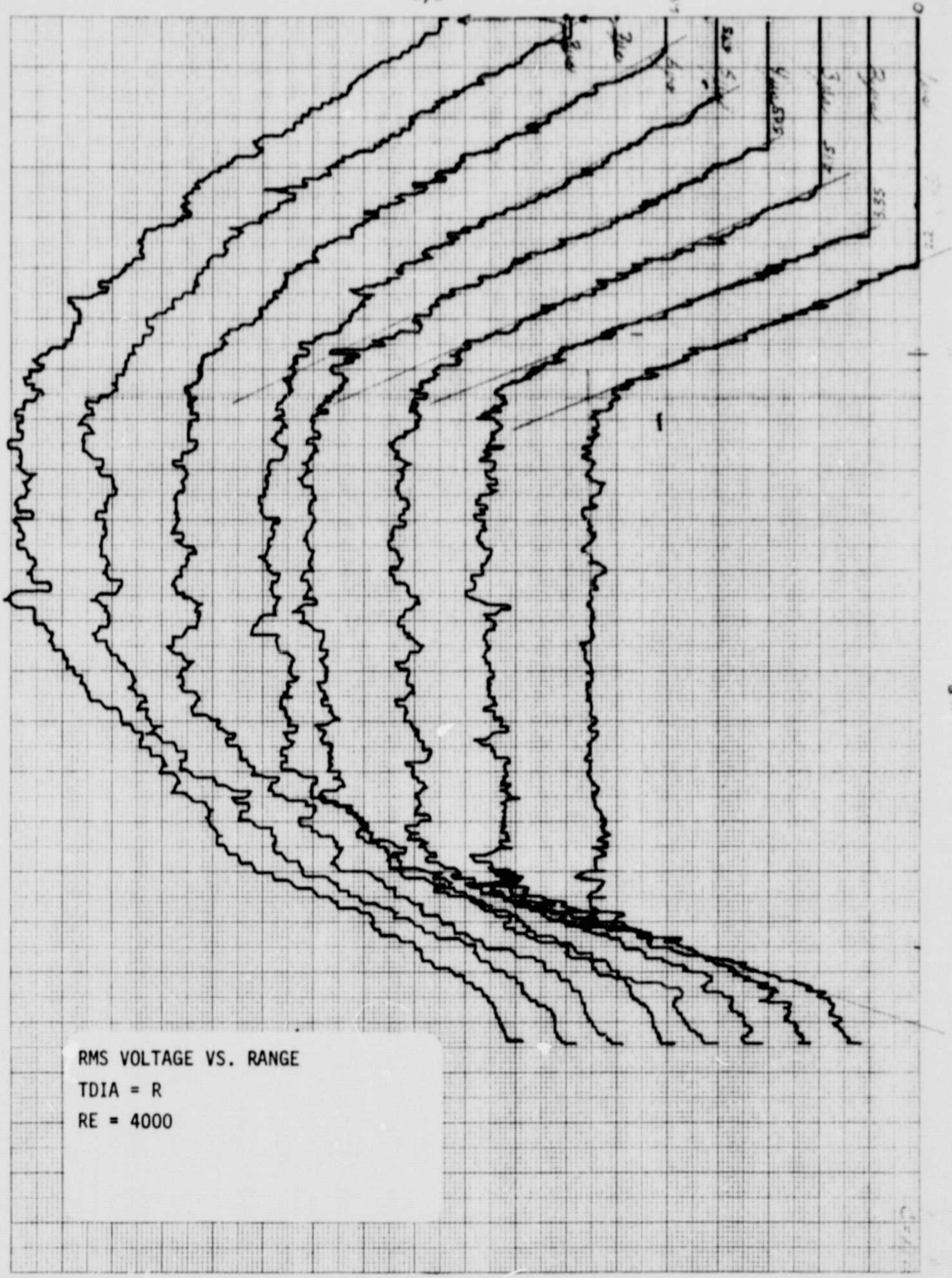

VELOCITY VS. RANGE
TRANSDUCER DIAMETER = R/2
RE = 1000
V_DOP = 25.4 cm/sec
V_STD = 26.3 cm/sec
D_ACT = 11.85 μsec
26

FIGURE 4



RMS VOLTAGE VS. RANGE

TDIA = R

RE = 4000

FIGURE 5

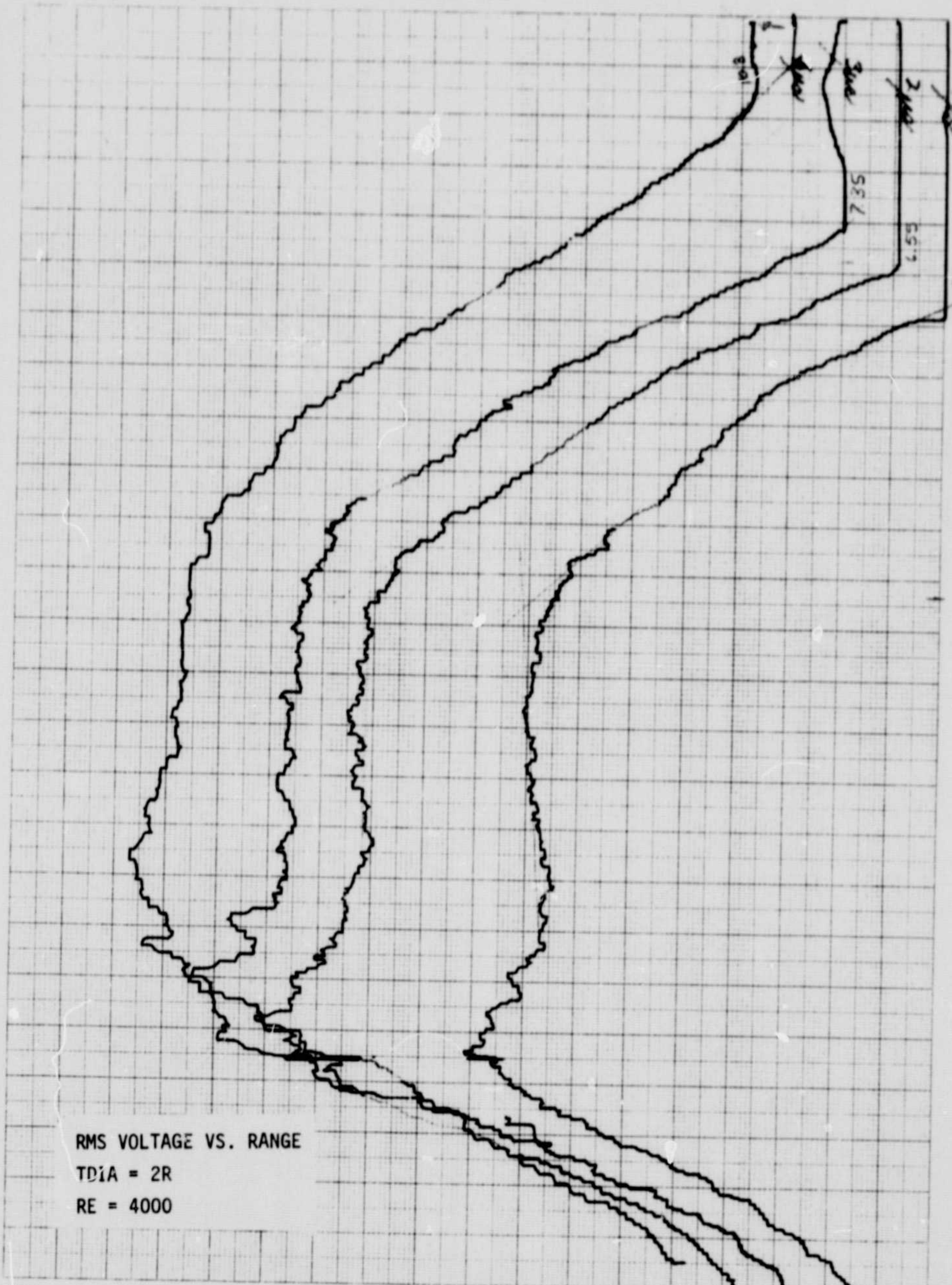


FIGURE 6

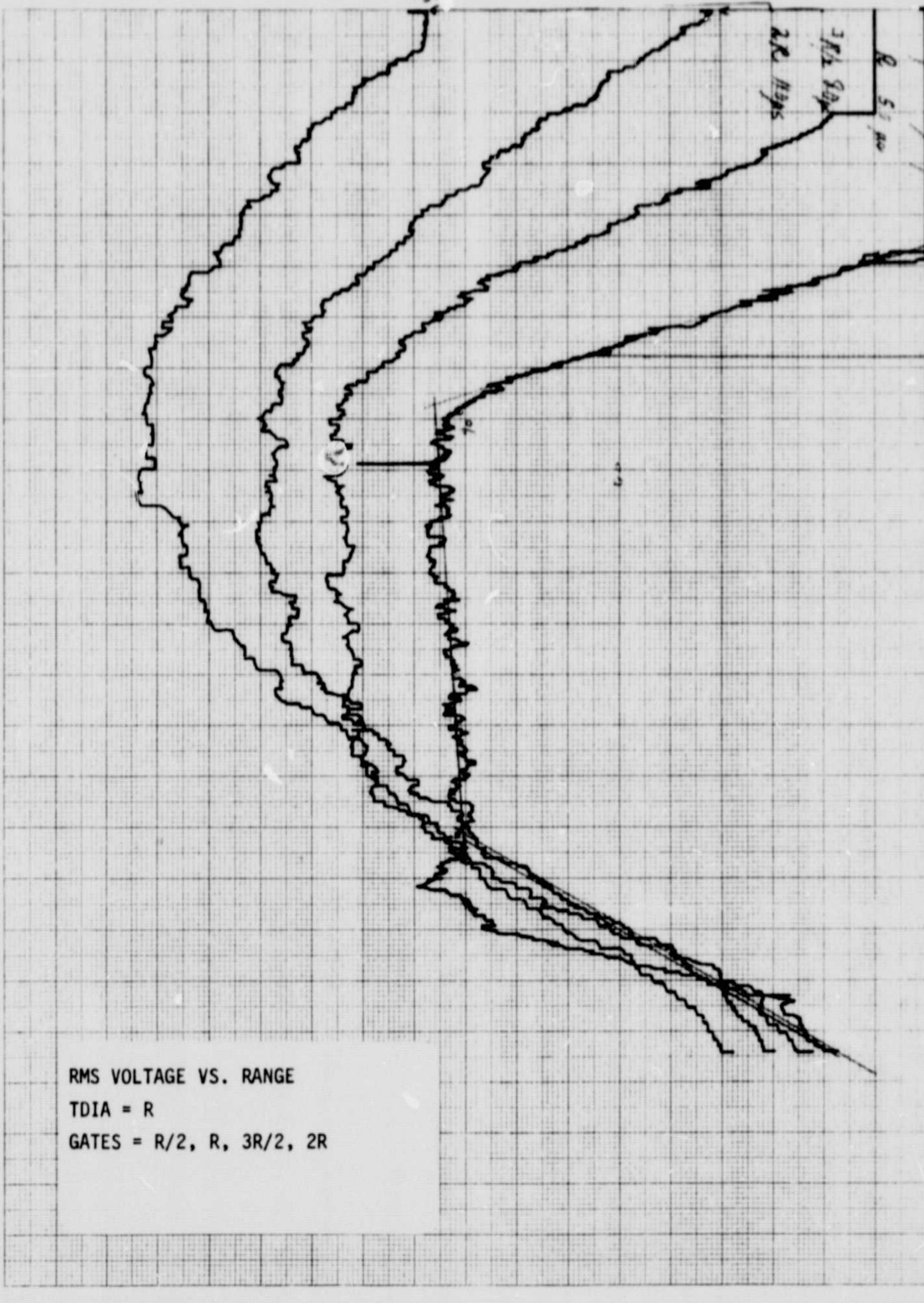


FIGURE 7

3. Velocity Profiles

Velocity profiles are obtained by manually scanning the sample function across the lumen and recording the output of the zero crosser (Histand, 1973). Typical velocity profiles for transducer R/2 for the 4 different gates are shown in Figure 4.

4. Results of Power Scans

Power scans in 1 μsec increments across the vessel diameter were measured for the three transducer diameters: R/2, R, 2R. Data for transducer R is shown in Figure 5 and for transducer 2R in Figure 6. The power curves for 2R were obtained with a flattened tube to provide an interface across the full transducer face. Figures 7 and 8 show power scans for transducer R and 2R respectively for gates of R/2, R, 3R/2, 2R.

5. Discussion

For a narrow gate (<R) small transducer (<R) one can accurately measure the vessel diameter. But as the gate widens from these values the power curves no longer plateau and it is impossible to estimate the half power points and thus the diameter.

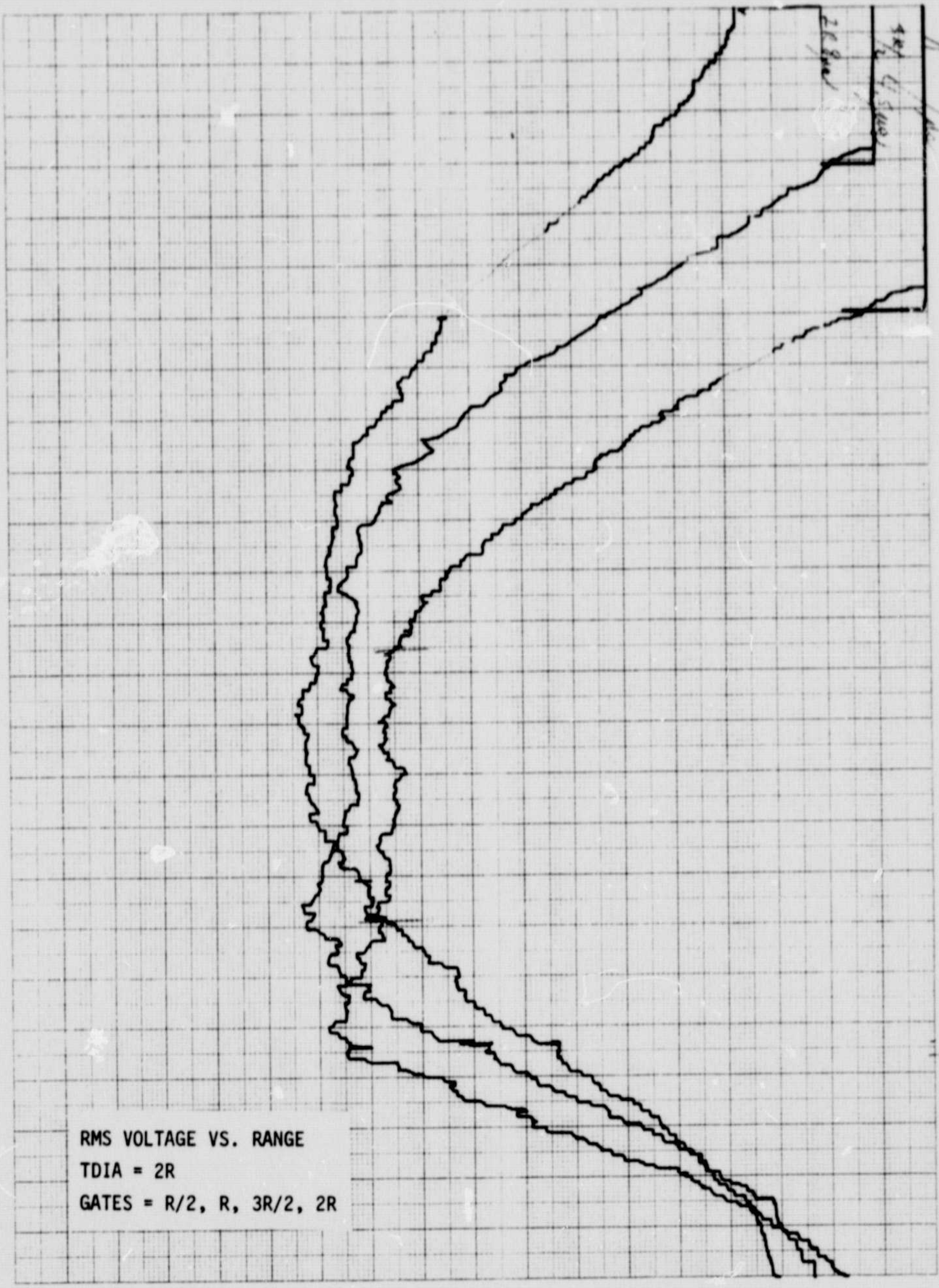


FIGURE 8

II. VELOCITY PROFILES AND FLOW CALCULATION

The purpose of these experiments was to assess the capability of the PUDVM as a velocity and flow measuring instrument in a simulated transmural application. The nondimensional parameters: transducer diameter, gate length, flow rate (Reynold's number), and vessel diameter were designated so that an investigator could judge the resolution of his measurements in an actual transcutaneous blood flow application. This experimental data is to be compared with the theoretical data described on pages 6-46 (Daigle, 1974). The following parameter and protocol was carried out with the end goal to determine velocity and flow measurement accuracy by various data processing schemes.

1. <u>Convolution/Boundary/Truncation Dialysis Tube - Transducer Experiment</u>

Parameters Controlled.

1. 7.7 mm dialysis tube 200 DIA entrance length; normalize radius = 1, for comparison of any vessel diameter, transducer diameter, PUDVM gate ratios.

2. Steady Flow; Re=1000, Re=1500 (laminar), Re=3000 (turbulent).

3. Transducer diameter (aluminum epoxy backing).

Dia	Normalized Diameter
7.7 mm	2R
3.85mm	R
1.98mm	R/2

4. PUDVM Pulse length = 8 cycles ~ τ_r = 1 μsec

5. Gate Settings (determined by power scans over flow/no flow interfaces).

length

R/2
R
3R/2
2R

Data.

1. RMS voltage curves (~power curves) for 1/2 power point determination.

2. Integrate profiles (standard computer program; diameter from max/min slope.

3. Integrate truncated profiles to known and half power diameters.

4. Small crystal wide gate calculation.

5. Compare velocity values, particular attention to full illumination wide gate.

Summary.

(3 transducers)x(4 gates)x(3 Re values) = 36 runs

Tabulated and plotted output.

2. Diameter Profile Integration Method

A technique for measurement of blood flow involves determination of the blood velocity profile across a diameter of the vessel under study. Since this technique requires measurements of local blood velocity at discrete points across the vessel, the PUDVM is employed. The procedure usually followed with single gate instruments is as follows: The transducer is positioned at a known angle to the vessel and the sample volume located outside the near wall of the vessel. The sample volume is then moved electronically across the vessel in discrete steps, with several heart cycles of blood velocity information recorded at each point. The EKG must be recorded simultaneously so that velocity measurements can be synchronized in time. Generally the quantity of data is such that computer processing of the velocity waveforms is required. The requirement that the Doppler angle be substantially less than 90° prohibits recording a velocity profile across a true diameter; however, for most measurements, the flow profiles can be assumed to be constant over the axial length in question. If a single gate PUDVM is used, the flow characteristics are also assumed to remain constant over the time required.

In addition to the limitations implied in the above mentioned assumptions, use of the diameter profile integration technique is subject to other errors. These errors may be divided into two categories: 1) experimental errors in applying the technique, and 2) resolution errors in the measurement of local velocity and vessel diameter with the PUDVM. The first category involves mostly experimental skill and technique while the second category involves inherent systematic errors.

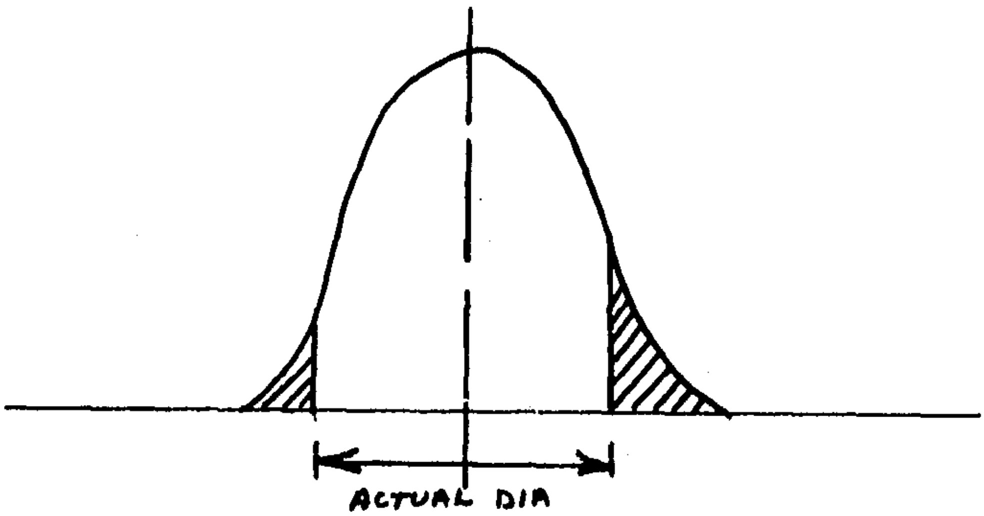
Certain assumptions are involved in calculating flow from the measured profile. First of all, the vessel geometry is assumed to by cylindrical over the measurement region. Secondly, the blood velocity field should have a degree of radial symmetry about the vessel axis. More specifically, the measured velocity profile should be valid for rotation about the vessel axis by ± 90°. Thirdly, the blood velocity vector is assumed to be parallel to the vessel axis at all times during the cardiac cycle, maintaining a constant Doppler angle to the sound beam. These latter two assumptions imply that the profile integration technique is not suitable for highly skewed velocity fields. See Daigle (1974) for details of profile integration method.

For transcutaneous measurements, the Doppler angle is usually set by two steps. The transducer is first adjusted for a null signal which orients the sound beam at 90° to the vessel axis. The Doppler angle is then set by rotating the transducer through a known angle in a plane which contains the vessel axis. This two step procedure requires a complicated transducer holder for measuring the angles involved and is time consuming. Also, refraction effects as the sound beam enters the tissue can introduce considerable error with this approach.

3. Profile Truncation and Integration

We know from theory and experiment that a velocity profile recorded with a PUDVM may exhibit tailing at the near and far walls of the vessel due to boundary and convolution error. This may cause an overestimation of vessel diameter and velocity at the region of

the walls. This is the rationale for the max/min slope method and reduction of velocity values at the wall described in method (Section 2). A second flow calculation method is known as profile truncation and integration and consists of truncating the measured velocity profile to the true vessel diameter (see below).



The truncated areas (shaded) are eliminated and the remaining profile is integrated as described previously. In these experiments the assumption of peak velocity at the centerline was made to permit wall location. This method therefore requires an independent, accurate measure of vessel diameter.

4. Diameter Gate Average Velocity Method

The diameter gate average velocity method utilizes a small transducer compared to the size of the vessel to obtain a centerline velocity with a narrow gate and a diameter average velocity with a wide gate encompassing the full vessel (Daigle, 1974).

The mean velocity $\overline{V}$ is given by

$$\overline{V} = \frac{V_p \overline{V}_c}{2V_p - \overline{V}_c}$$

where V_p is the centerline velocity and $\overline{V}_c$ is the average velocity along a thin sample beam across a diameter.

III. VELOCITY SCANS - RESULTS

1. Velocity Profile Data

Nine figures summarize the velocity scan data. Figures 9, 10, 12, 13, 15, and 16 exhibit scans for various gates for laminar flow while Figures 11, 14, and 17 exhibit turbulent profiles. The theoretical profile is shown on each figure as a dotted line and the measured profiles are indicated with their gate lengths. The transducer diameter and Reynold's number are indicated in the upper right hand corners of the figures. All data are nondimensional with the nondimensional radius on the abcissa and the nondimensional velocity on the ordinate. The broadening of the profiles with increasing gate length is obvious on all graphs. The boundary error effect (Daigle, 1974) is subtle but is more noticeable for gate lengths of ~ 3R/2 (see Figure 1). These figures should be compared with Figures 2-8, 2-9, 2-10, and 2-11 (Daigle, 1974).

2. Velocity Scans - Discussion

The PUDVM measures centerline velocity accurately for $R_{transducer} < R/2_{vessel}$ and a gate $< R/2_{vessel}$. Under this constraint the centerline velocity errors are generally less than 4%. When the gate is increased to R, 3R/2, and 2R the error in centerline velocity is 7%, 11%, and 18% respectively. Figure 9 shows the velocity profiles for transducer R/2 and we observe the profile broadening and C_L velocity dimunition with increasing gate. The measured profile appears somewhat narrower than the actual profile for $\tau_{gate} = R/2$. For a Reynold's number of 3000 (turbulent), the smaller gates overestimate the C_L velocity by approximately 10%. The assumed profile

is quite blunt and decreased bluntness would provide more accurate results. For the turbulent case it is difficult to accurately choose a profile <u>vis a vis</u> laminar flow (see next section).

For a transducer diameter R we see a generally decreased accuracy in C_L velocity measurements, (Figures 4, 5, and 6) except for the turbulent case where the C_L error is ~ 6%.

For a transducer diameter 2R (full vessel illumination) the accuracy of C_L velocity measurements drops off still further as expected. However, for the turbulent flow case the velocity is measured quite accurately for all gates, but again this is for a somewhat arbitrary choice of the turbulent velocity profile.

For a wide gate condition, i.e., τ_g ~ 2R the measured centerline velocity for different transducer diameters is:

	Dia	Gate	C_L Velocity Laminar	C_L Velocity Turbulent
1)	R/2	2R	.82	1.04
2)	R	2R	.77	.97
3)	2R	2R	.73	.96

We are most interested in case 3, the full vessel illumination, wide gate condition. Here we find that we overestimate the mean velocity by nearly 50%. This result can be attributed to the use of circular transducers with overestimation of central core velocities. This result is in agreement with all wide gate measurements we have made to date using circular transducers.

3. <u>Calculation of Turbulent Profile: Reynolds Number = 3000</u>

From Schlicting (1974 Ed. p. 563) we have the following profile

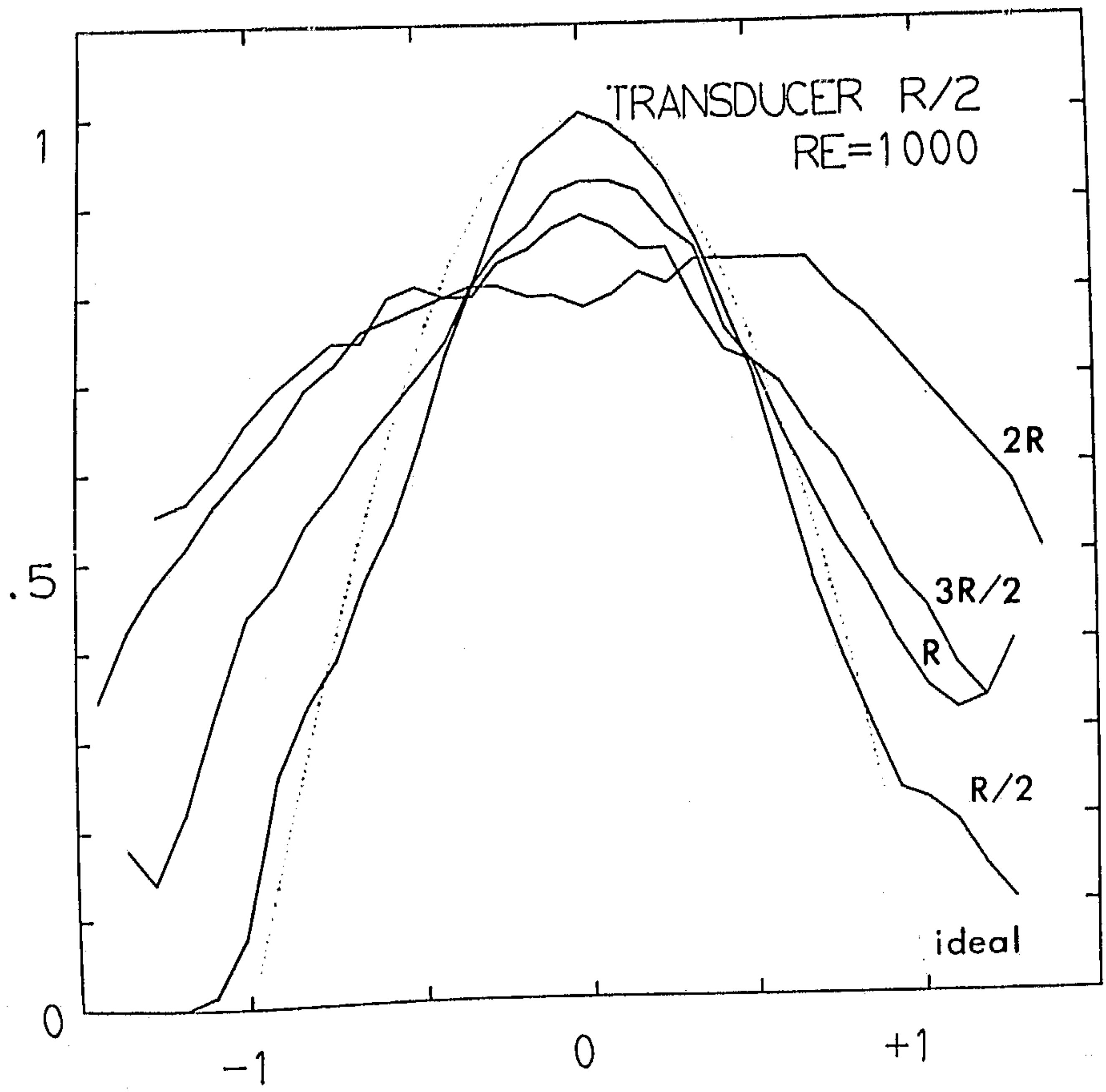


FIGURE 9

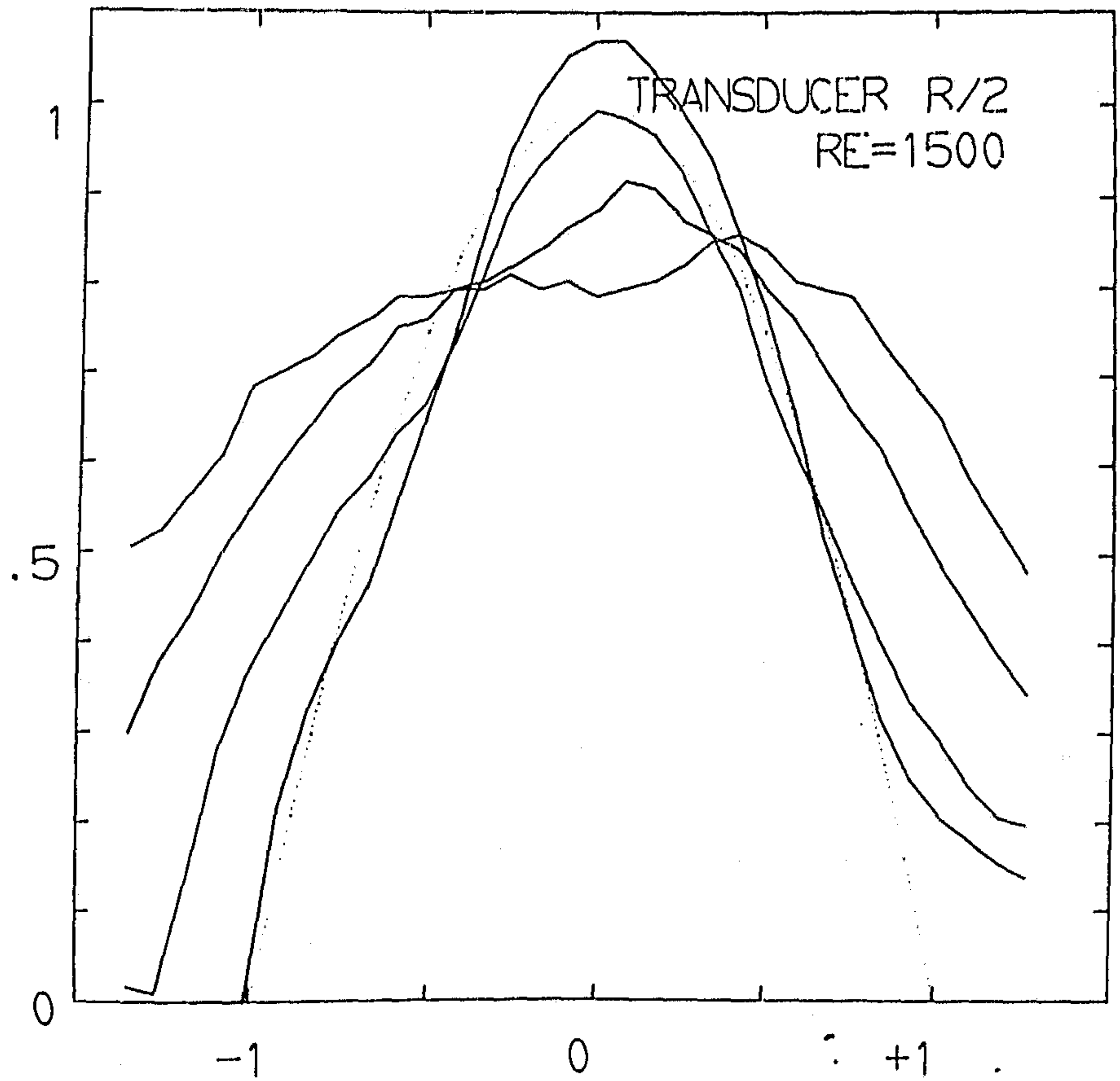


FIGURE 10

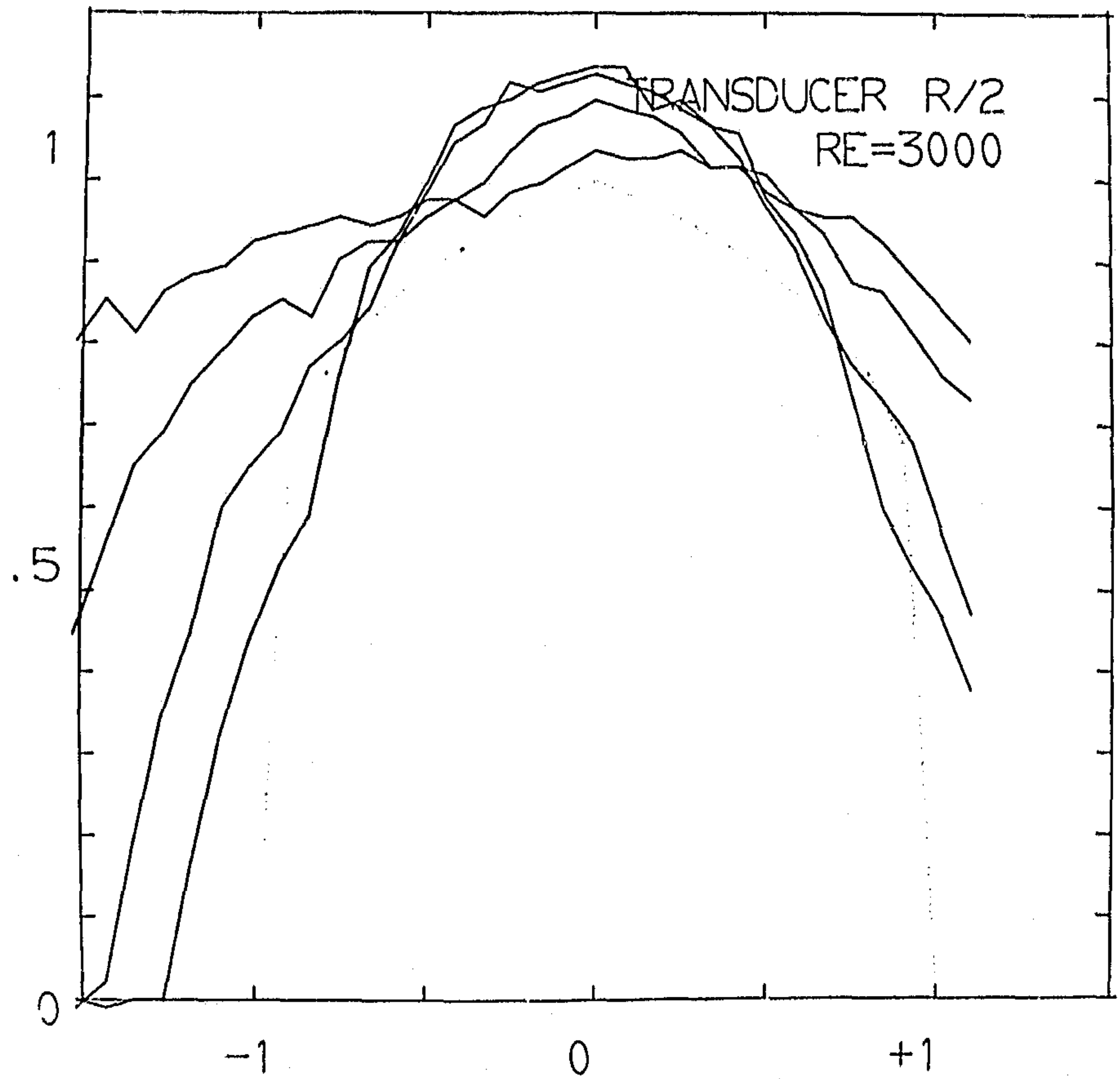


FIGURE 11

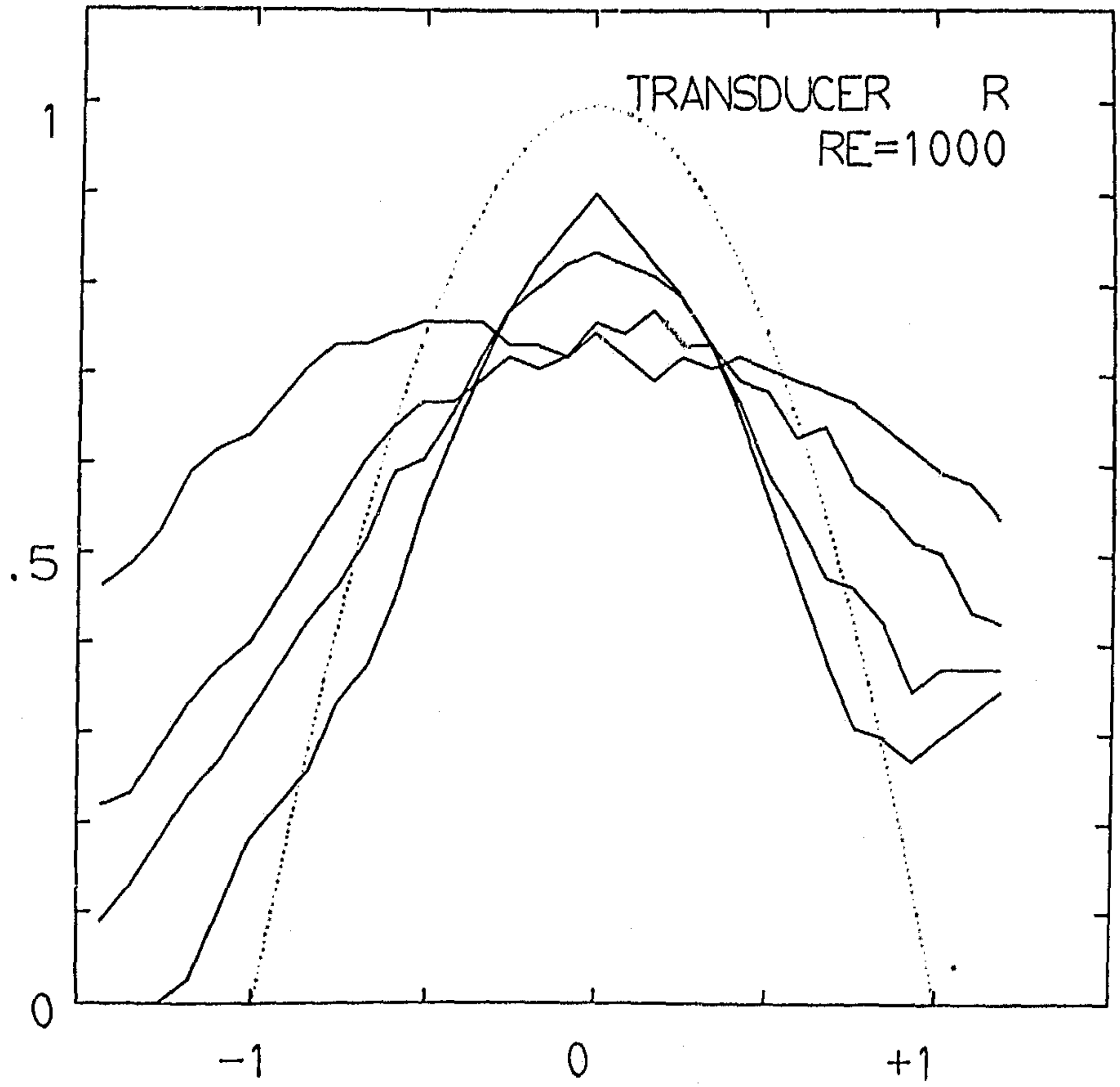


FIGURE 12

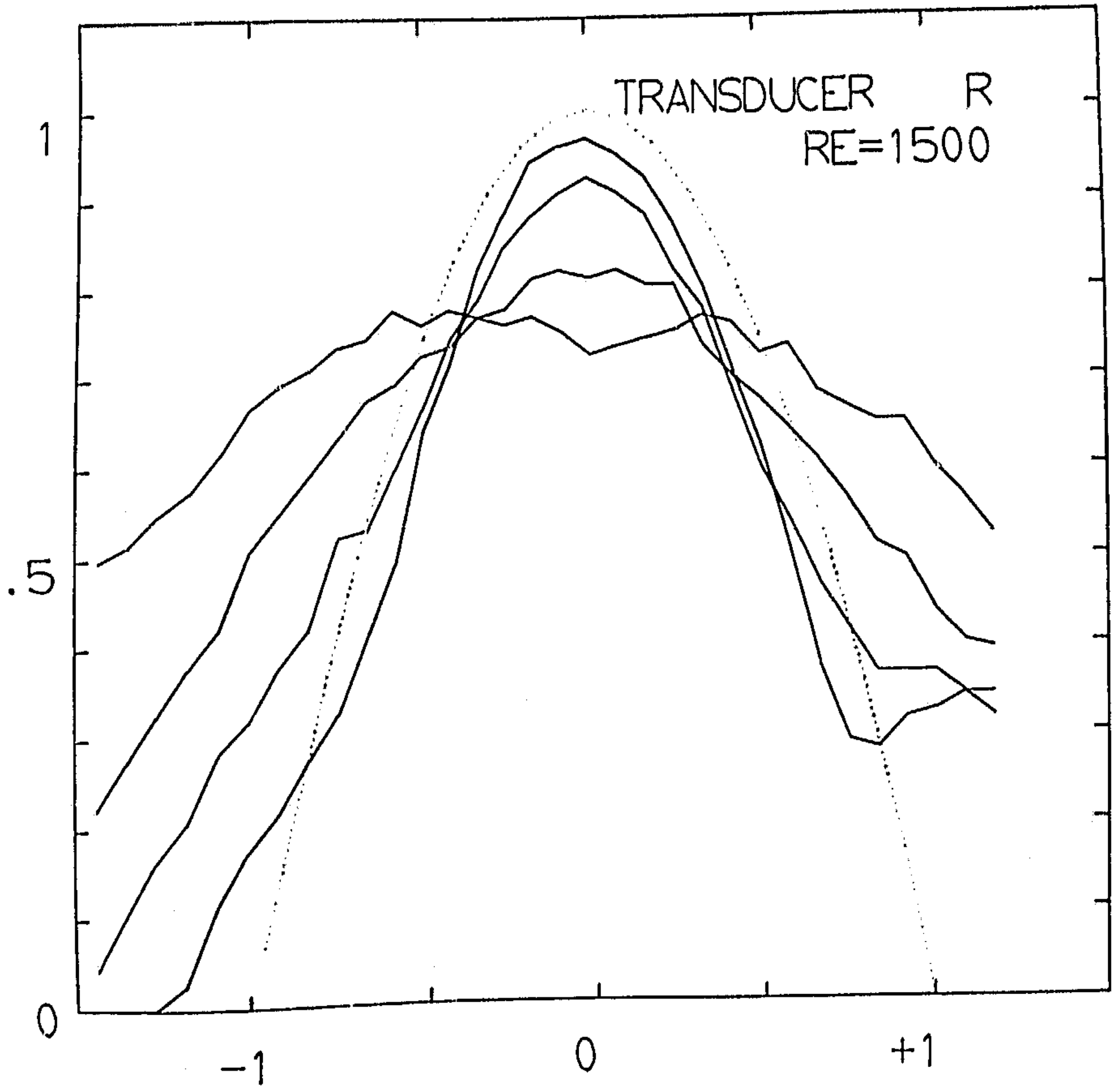


FIGURE 13

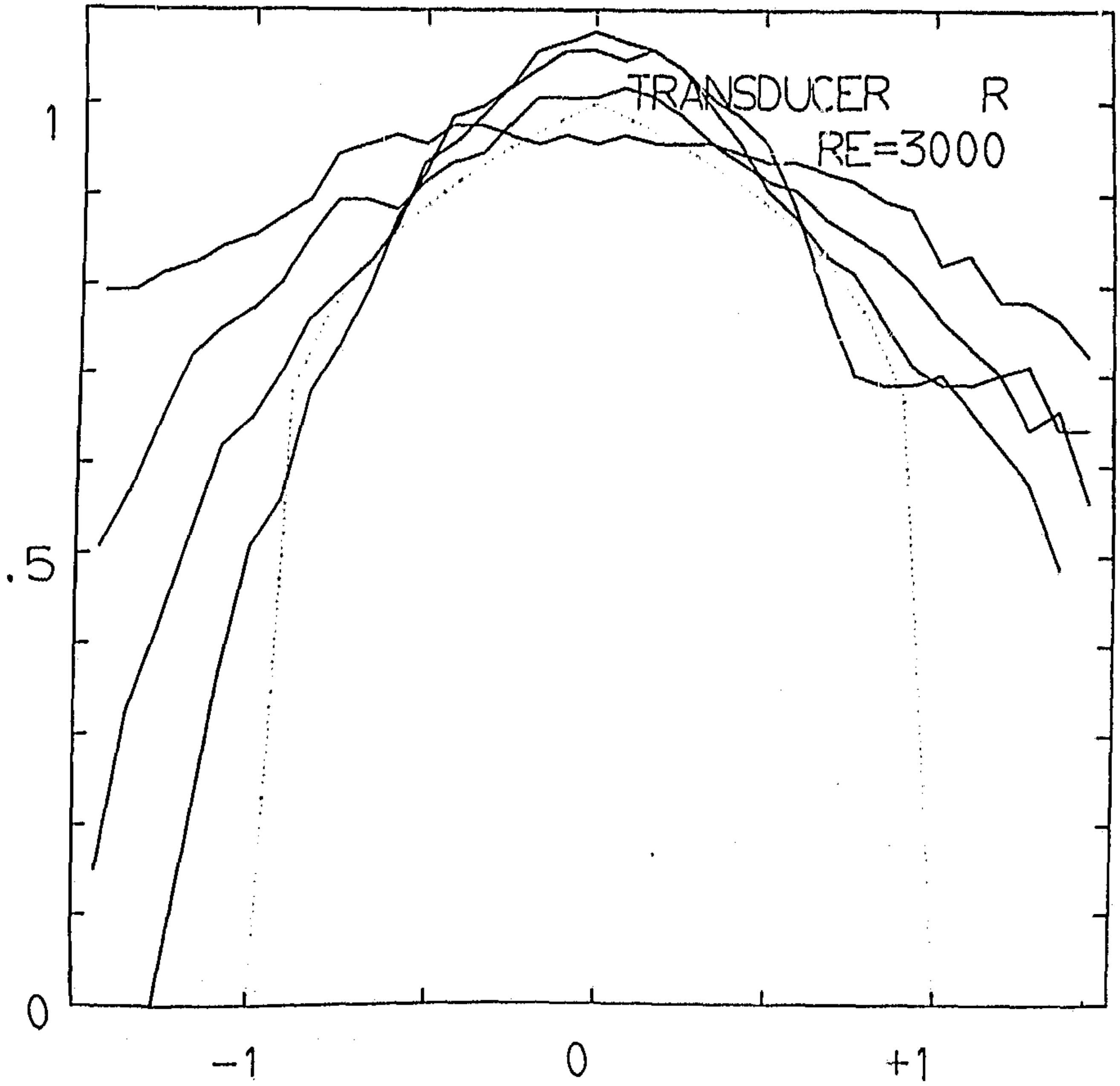


FIGURE 14

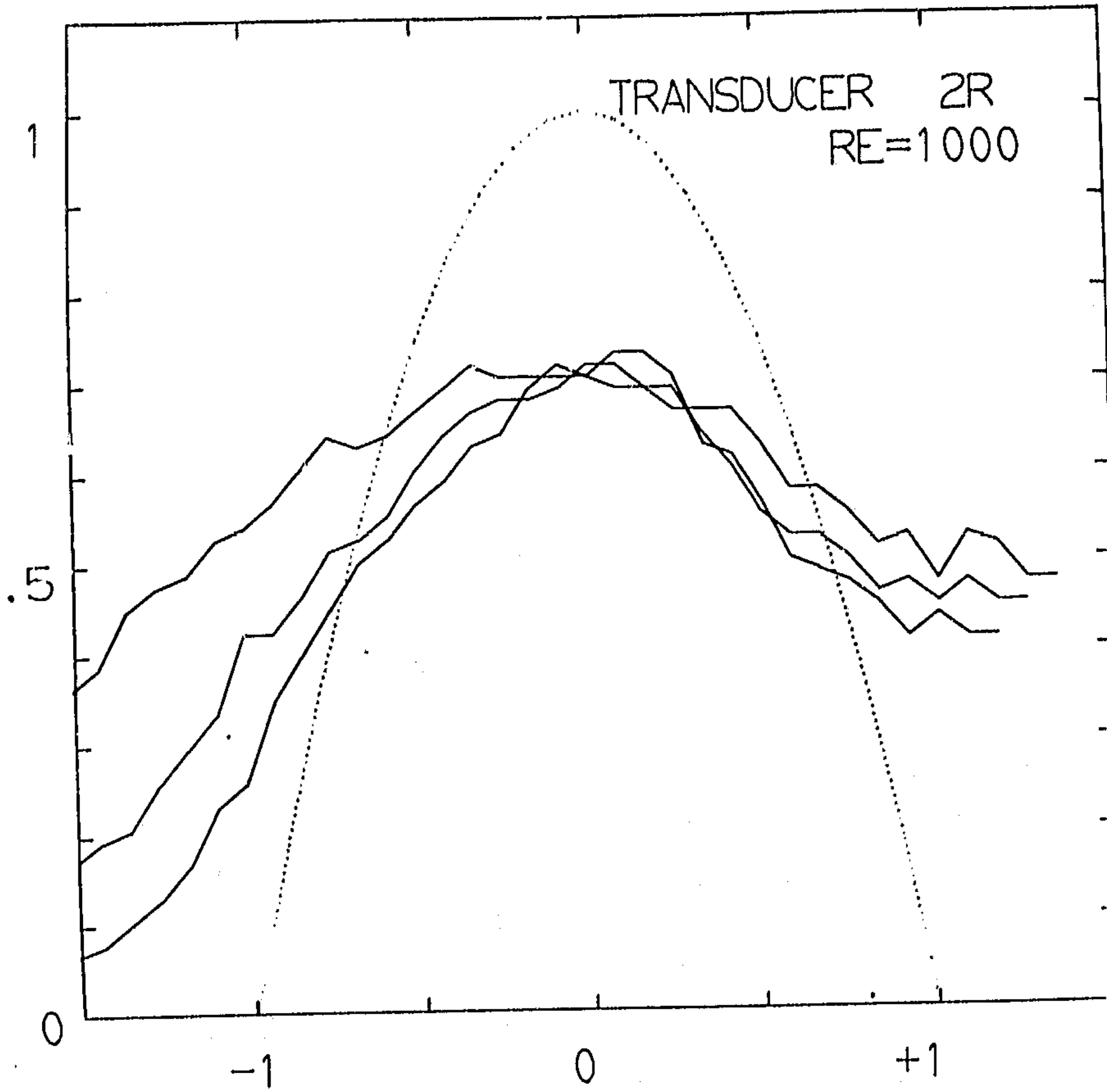


FIGURE 15

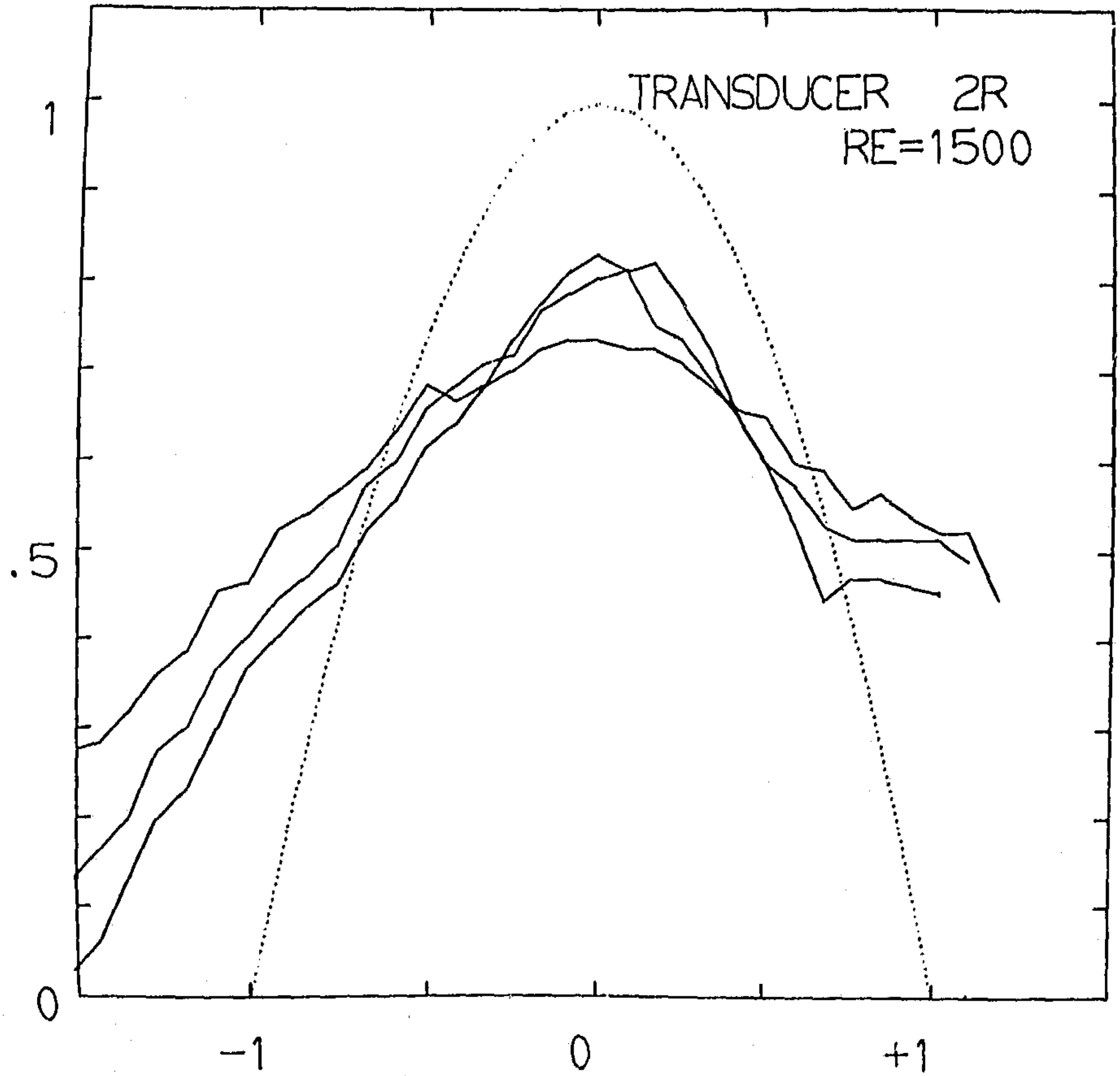


FIGURE 16

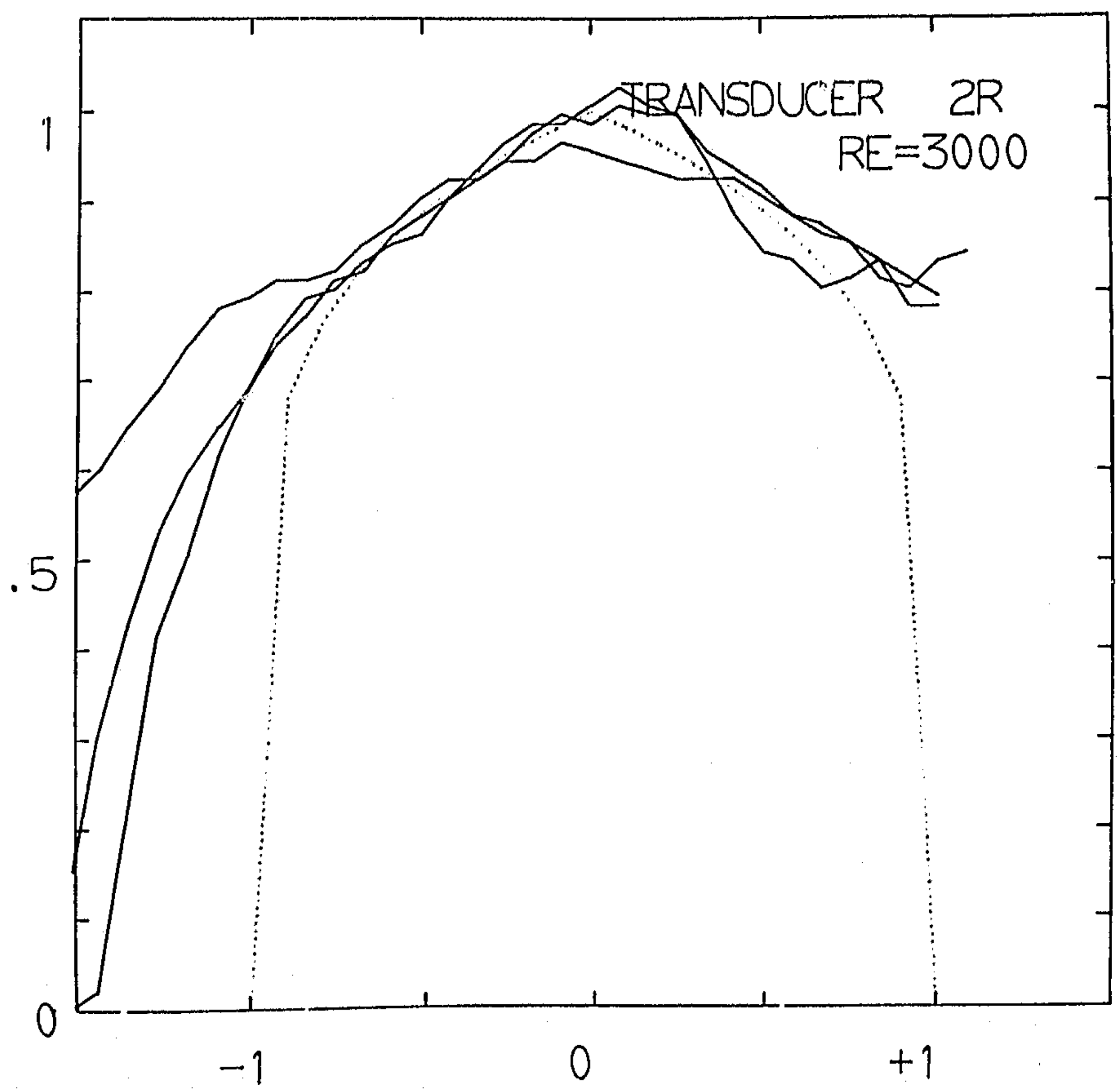


FIGURE 17

given for turbulent flow, Re ~ 3000:

$$u(r) = V_o\left(1 - \frac{r}{R}\right)^{1/6} \tag{1}$$

Knowing the flowrate in our experiment (used to determine Re = 3000) we can integrate (1) to relate Q, the flow, to the centerline velocity for the turbulent profile.

$$Q = 2\pi V_o \int_0^R \left(1 - \frac{r}{R}\right)^{1/6} r\,dr$$

integrating this expression

$$Q = .3956(2\pi V_o R^2)$$

therefore

$$V_{C_L} = V_o = \frac{Q}{.7902\pi R^2}$$

For a flow Q of 18.12 corresponding to a Reynold's number of 3000, the centerline velocity is 49.18 cm/sec. However, unlike the laminar flow case where we have substantial theoretical and experimental background to substantiate the parabolic velocity profile, in turbulent flow there is more room for error in choosing the profile shape as above. Nevertheless, the profile we have chosen should be close to the real profile.

4. Volume Flow Comparison

The primary purpose of these experiments was to determine the performance accuracy of the PUDVM as a flowmeter. To carry out this objective, we varied transducer diameter, gate length, and Reynold's number and calculated volume flow by 1) profile integration where the wall locations are calculated by the mini/maxi slope method, 2) profile integration truncating the velocity at the walls where wall locations are set by knowing the true diameter in one case and by measuring the half power diameter in the second case, and 3) the small transducer-wide gate method. The results of these experiments are summarized in Table I where all data has been normalized to actual measured volume flow (by rotimeter and volume collection).

For transducer R/2 increasing the gate from R/2 to 2R produces increases in calculated volume flow as expected, but the noteworthy result is that the volume flow estimate is most accurate using the truncation method regardless of the comparable gate length. This result is consistent also for transducers R and 2R. It is also interesting to note that volume flow can be more accurately measured for turbulent flow, where presumably the flattened profile helps improve the accuracy by eliminating steep velocity gradients across the full vessel lumen. To conclude, tolerable calculations of volume flow for all Reynold's numbers were obtained for transducer R/2 with gates R/2, R; transducer R with gates R/2, R, 3R/2; and transducer 2R with gates R, 3R/2, 2R. The R/2 gate for transducer 2R could not be obtained due to high initial velocity values. Compare these results with data from Table 2-2 (Daigle, 1974).

VOLUME FLOW COMPARISONS I

	FUNCTION LENGTH	ACTUAL VOLUME FLOW	VOLUME FLOW FROM COMPUTER PROGRAM MAX/MIN SLOPE			VOLUME FLOW FROM VELOCITY PROFILE TRUNCATED TO ACTUAL~1/2 POWER DIAMETER			CENTERLINE VELOCITY DOPPLER/ACTUAL CENTERLINE VELOCITY		
			RE=1000	RE=1500	RE=3000	RE=1000	RE=1500	RE=3000	RE=1000	RE=1500	RE=3000
TRANSDUCER R/2	R/2	1.0	.85	.86	1.00	.97	1.02	.98	1.00	1.07	1.14
	R	1.0	.95	1.01	1.32	1.17	1.11	1.03	.93	.99	1.13
	3R/2	1.0	1.69	1.70	1.63	1.30	1.34	1.10	.89	.92	1.10
	2R	1.0	2.05	2.01	1.55	1.47	1.45	1.14	.82	.82	1.04
TRANSDUCER R	R/2	1.0	.42	.47	1.40	.83	.89	.96	.90	.97	1.08
	R	1.0	.59	.46	1.67	1.00	1.03	1.01	.84	.93	1.06
	3R/2	1.0	.91	1.36	1.57	1.14	1.20	1.05	.77	.82	1.02
	2R	1.0	1.86	1.68	1.19	1.32	1.35	1.10	.75	.78	.97
TRANSDUCER 2R	R	1.0	.53	.89	.79	.95	1.02	1.00	.73	.83	1.03
	3R/2	1.0	.72	.82	.86	1.01	1.08	1.02	.72	.81	1.01
	2R	1.0	1.22	.96	1.38	1.15	1.14	1.03	.72	.74	.96

5. DIAMETER - Gate Average Velocity

From Daigle (1974)

$$\bar{V} = 1/2\ V_p$$

$$\bar{V}_c = 2/3\ V_p$$

using data obtained with transducer diameter R/2

Table I:

$$\bar{V}_c = .82 \text{ for gate } 2R$$

$$V_p = 1.0 \text{ for gate } R/2$$

therefore calculating $\bar{V}$

$$\bar{V} = \frac{V_p \bar{V}_c}{2-\bar{V}_c} = \frac{.82}{1.18} = .70$$

$$\bar{V} = .70$$

Note again this is a 40% overestimate of $\bar{V}$ and thus volume flow. Although the transducer is slightly larger than R/4, this overestimation is not a strong recommendation for the diameter - gate average velocity method.

Wide Gate (2R) Centerline Velocities

Transducer	RE	"$\overline{V}$"	$\overline{V}_{actual}$	% overest
R/2	1000	.82	.50	44
	1500	.82	.50	44
	3000	1.04	.81	28
R	1000	.75	.50	50
	1500	.78	.50	56
	3000	.97	.81	19
2R	1000	.72	.50	44
	1500	.74	.50	48
	3000	.96	.81	18

We can conclude that a rectangular crystal transducer is required for accurate wide gate mean velocity measurements in contrast to the circular transducer whose results are shown here.

IV. CURRENT WORK

1. Ultrasonic Transducer Power Emission

   A Cahn Electrobalance model 4600 special has been adapted to measure energy emitted by ultrasonic transducers used in this research. The purpose of these measurements will permit us to quantitate exposure levels in the event the transducers may be applied to human patients.

2. The electronic specifications for the pulsed Doppler electronics employing the wide gate method are being set. Fabrication will occur following specification of emitted power and wide band signal processing.

3. *In vivo* flow calibrations are being performed to establish the accuracy of the wide gate method for blood flow measurement.

V. BIBLIOGRAPHY

Daigle, R. E., C. W. Miller, F. D. McLeod, M. B. Histand, M. K. Wells, "Transcutaneous Measurement of Volume Blood Flow," NASA Report, August 1, 1974.

Histand, M. B., C. W. Miller, F. D. McLeod, "Transcutaneous Measurement of Blood Velocity and Flow, Car. Res. 7: 703 (1973).

McLeod, F. D. and M. Anliker, "A Multiple Gate Pulsed Doppler Flowmeter," IEEE Sonics and Ultrasonics Symp. Miami Beach, p. 51.

Schlieting, Hermann, Boundary Layer Theory, 6th ed., McGraw Hill, 1968, p. 563.